

Taiwan EXperiment On Neutrino – History, Status and Prospects

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We present an overview of the foundation, evolution, contributions and future prospects of the TEXONO Collaboration and its research programs on neutrino physics and dark matter searches at the Kuo-Sheng Reactor Neutrino Laboratory in Taiwan and, as a founding partner of the CDEX program, at the China Jinping Underground Laboratory in China.

1 Introduction

The themes of the research programs of the TEXONO (Taiwan EXperiment On Neutrino) Collaboration are on the studies of low energy neutrino and dark matter physics. The Collaboration realized the first particle physics experiment in Taiwan at the Kuo-Sheng Reactor Neutrino Laboratory (KSNL) and, through the process, the first basic research collaboration among researcher scientists from Taiwan and China [1]. The efforts of the starting decade catalyzed and laid the foundation to the establishment of the China Jinping Underground Laboratory (CJPL) in China, together with its first generation China Dark matter EXperiment (CDEX).

The history and evolution of the TEXONO story is given in the following Sections. The scientific objectives, status, results and prospects of the neutrino physics program at KSNL, as well as the underground physics program at CJPL, are discussed. Also surveyed is the theory program inspired by the experimental activities.

2 History and Evolution

2.1 Foundation

Phenomenal growth in basic and applied research has been taking place in the Asia Pacific region in the decades of 1980's and 1990's [2]. As the economy strengthened, research projects in new and advanced subjects were initiated. Research infrastructures, resources and positions were made available. Research directions and

traditions were explored and defined, with far-reaching consequences beyond their original subject matters.

Activities in experimental particle physics started in Taiwan in the early 90's. The starting projects involved participation in international experiments, including L3, CDF, Belle, AMS, RHIC-PHOBOS, with contributions on various detector hardware, data acquisition software and data analysis projects.

It became natural, almost inevitable, that serious thoughts were given to an attempt to “perform an experiment at home”, where local researchers would take major responsibilities in its conception, formulation, design, construction, execution and scientific harvest. Chang Chung-Yun (University of Maryland, while on a sabbatical year at the Academia Sinica (AS)) and Lee Shih-Chang (AS) initiated a research program towards such goals in 1996. This ambition soon found a resonating chord with Zheng Zhi-Peng (then Director of the Institute of High Energy Physics (IHEP), Beijing, China) who mobilized his Institute to participate. Therefore, the project would carry with it an additional pioneering spirit of being the first collaboration in basic research among scientists from Taiwan and China, standing on a decade of mutual visits and academic exchanges. It was obvious that many scientific, technical, administrative and logistic issues have to be ironed out to make advances on these virgin grounds.

The author (H.T. Wong) was recruited by AS in 1997 to take up the challenges of realizing such visions. The Chinese groups were headed by Li Jin (senior physicist at IHEP). The

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TEXONO Collaboration was formed, where the founding partners comprised institutes from Taiwan (AS, Institute of Nuclear Energy Research, Taiwan Power Company Nuclear Station II, National Taiwan University and National Tsing-Hua University), China (IHEP, China Institute of Atomic Energy (CIAE), Nanjing University) and the USA (University of Maryland). The operation center has since been at AS in Taiwan, and the AS-group has been leading and coordinating the efforts.

By the mid-2000's, the TEXONO Collaboration has established research facilities and infrastructures, formulated interesting research programs and produced world-level scientific results. International partners from India (Banaras Hindu University) and Turkey (Middle East Technical University, Dokuz Eylül University) joined the research program and contribute in various major items. In particular, an international graduate student training scheme was set up as part of the operation. Numerous graduate students from China, India and Turkey have stationed long-term at AS to pursue research within of the TEXONO program and produced research theses from the outcomes.

2.2 Research Directions and Strategies

Anomalous results from solar and atmospheric neutrino measurements [3] were gathering momentum in the 1990's, cumulating in the presentation of evidence of neutrino oscillation by the Super-Kamiokande experiment in 1998 [4]. The case of having missing energy density in the Universe in form of Dark Matter was also getting increasingly compelling. Non-accelerator based particle physics was at its early stage and constituted a good opportunity for a start-up research group to move into.

Reactor neutrino was identified in the foundation days as a realistic platform for the TEXONO program. One needs neutrino sources to study neutrino physics, and reactor neutrino is an intense and understood neutrino source, available for free as a by-product of commercial power reactor operation, and allows systematic studies and control through Reactor ON/OFF comparison. And – most importantly, there are operating power reactor plants in Taiwan within

comfortable commuting distance from AS.

The early target was a long baseline reactor neutrino oscillation experiment [5]. Feasibility studies and a liquid scintillator R&D program were pursued [6] in the first years. However, intense competition in the world stage called for the necessity to re-consider such directions. The Chooz experiment just began to produce results while KamLAND was already advanced in securing resources and has started hardware construction [4]. It was necessary for the TEXONO program to identify its niche, based on honest assessment of its strength in terms of accessible resources, manpower pool, experience and expertise.

The aspired goal was that the first experiment should on its own be able to produce valid scientific results. The science subjects evolved to the studies of neutrino interactions and properties, which benefit from a location close to the reactor core having an intense neutrino flux. This would be complementary to the neutrino oscillation programs being pursued world-wide [3], where the experiments would require baseline of kilometers or longer, translating directly into large detector size while the optimal detector technology (liquid scintillator) and its technical details have mostly been defined.

Reactor neutrino experiments before TEXONO were all based on measurements of events at MeV_{ee} (electron-equivalent energy eV_{ee} is used throughout this article as unit to detector response, unless otherwise stated) or above, therefore only sampling the tail of the reactor neutrino spectra. The TEXONO program would open the previously-unexplored detector window in the low energy regime. To realize these goals, we selected detector techniques where “the best technology is in the market” – namely, scintillating crystal detectors [7] and germanium (Ge) ionization detectors. With the benefits of hindsight, this important strategic decision allowed a new group with “zero background” in running a particle physics experiment to get lifted off and start its flight in a relatively short time.

The stage is thus set for the construction of the KSNL reactor laboratory and for the formulation of the details of its research programs.

As a record and for completeness, the TEXONO group, together with international partners, has considered the possibility and per-

formed feasibility studies for a reactor measurement [8] of the oscillation angle θ_{13} in the early days of its formulation in 2003. The merits with both the Kuo-Sheng Power Plant and the new “Nuclear Station IV” at Lung-Men were investigated. Compared with other site proposals, the Kuo-Sheng location lacks high mountains in the appropriate distance, whereas Lung-Men Power Plant, while having larger overburden, suffered from the lack of a definite plan of starting operation (it *still* does not operate in 2016!). In addition, both plants are two-cores facilities, weak in total neutrino flux compared to other international proposals based at locations with six cores or more. Accordingly, this line of research was not pursued after the initial round of investigations. A Taiwan team with three university groups subsequently participated in the Daya Bay experiment which provided the best measurement of θ_{13} [9] at the six-core Daya Bay Nuclear Power complex in southern China.

3 Kuo-Sheng Reactor Neutrino Laboratory and the TEXONO Research Programs

3.1 The Facility

The Kuo-Sheng Reactor Neutrino Laboratory (KSNL) is located at a distance of 28 m from the core #1 of the Kuo-Sheng Nuclear Power Station operated by the Taiwan Power Company at the northern shore of Taiwan. The nominal thermal power output is 2.9 GW. Conceptual design discussions were initiated in 1997. First physics data taking started in July 2001. A schematic view is depicted in Figure 1a.

A multi-purpose “inner target” detector space of 100 cm×80 cm×75 cm is enclosed by 4π passive shielding materials which have a total weight of about 50 tons. The shielding provides attenuation to the ambient neutron and gamma background, and consists of, from inside out, 5 cm of OFHC copper, 25 cm of boron-loaded polyethylene, 5 cm of steel, 15 cm of lead, and cosmic-ray veto scintillator panels. The schematic layout of the shielding structure is shown in Figure 1b.

Different detectors can be placed in the inner space for the different scientific programs. The detectors are read out by a general pur-

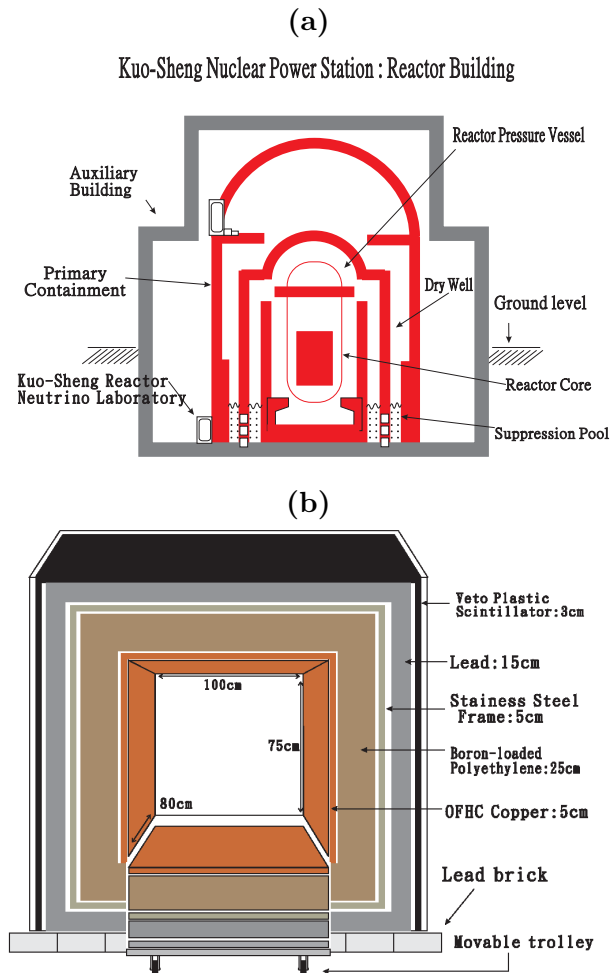


Fig. 1: (a) Schematic side view, not drawn to scale, of the Kuo-Sheng Nuclear Power Station Reactor Building, indicating the experimental site. The reactor core-detector distance is about 28 m. (b) Schematic layout of the general purpose inner target space, passive shieldings and cosmic-ray veto panels.

pose electronics and data acquisition (DAQ) systems. Earlier versions of home-made electronics and VME-based DAQ [10] evolves into current version with a commercial-based PXI-DAQ system with Flash Analog-to-Digital converters and Field Programmable Gate Array which provides real time processing capabilities, with DAQ-software via LabView packages.

The reactor laboratory is connected via telephone line (internet access not available to the reactor buildings) to the home-base laboratory at AS, where remote access and monitoring are performed regularly. The data storage capacities are about 2 Tbytes *in situ* at KSNL and 500 Tbytes at the operation base at AS.

3.2 Reactor Neutrino Source

The standard operation of the Kuo-Sheng Power Plant includes about 18 months of Reactor ON time at nominal power followed by about 50 days of Reactor outage OFF period. Reactor operation data on the thermal power output and control rod status as functions of time and locations within the core are provided, when necessary, to the experiment by the Power Station.

The $\bar{\nu}_e$'s emitted in power reactors are predominantly produced through β -decays of (a) the fission products, following the fission of the four dominant fissile isotopes: ^{235}U , ^{238}U , ^{239}Pu and ^{241}Pu , and (b) ^{239}U , following the neutron capture on the ^{238}U fuel: $^{238}\text{U}(n,\gamma)^{239}\text{U}$.

The reactor neutrino spectra ($\phi(\bar{\nu}_e)$) as function of neutrino energy (E_ν) due to the individual components are summed as a function of time according to the relative contributions per fission [11, 12], and a typical combined reactor neutrino spectrum is shown in Figure 2a. The typical total flux at KSNL site is $6.4 \times 10^{12} \text{ cm}^{-2}\text{s}^{-1}$.

3.3 Low Energy Neutrino Physics

Investigations of neutrino properties and interactions can reveal physics within the Standard Model (SM) and probe new physics beyond it (BSM). The KSNL site provides an intense flux of $\bar{\nu}_e$ and is ideal for such investigations. The nuclear and electron recoil differential spectra due to reactor $\bar{\nu}_e$ as a function of measurable recoil energy T are depicted in Figure 2b, showing signatures due to both SM interactions and BSM neutrino electromagnetic effects at the current

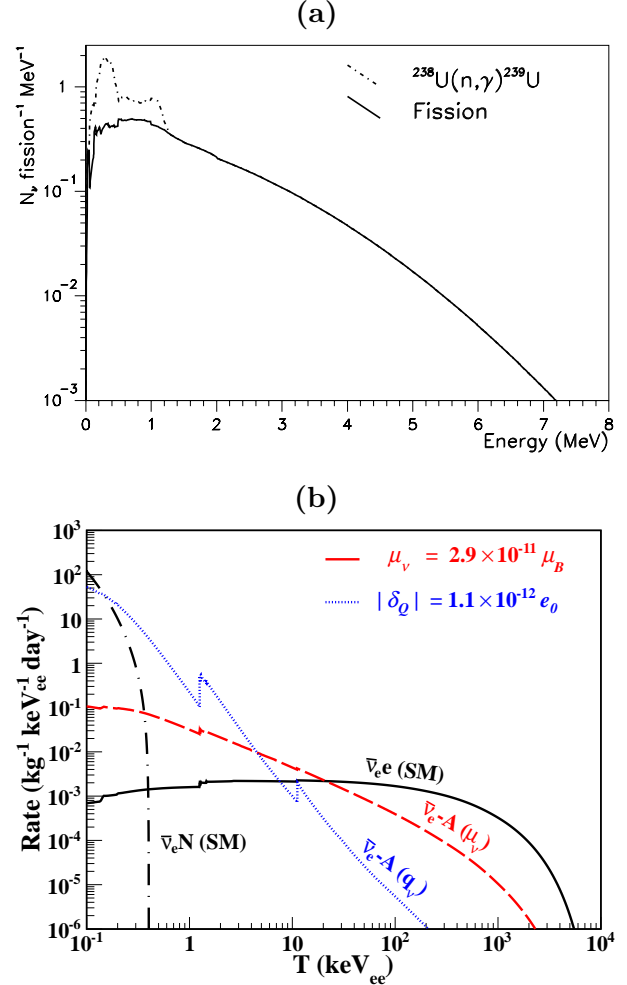


Fig. 2: (a) Typical total reactor $\bar{\nu}_e$ spectrum [11, 12], normalized to per fission in a 1-MeV energy bin. (b) The observable recoil spectra due to reactor- $\bar{\nu}_e$ interactions on Ge target via Eq. 1 with $\phi(\bar{\nu}_e) = 10^{13} \text{ cm}^{-2}\text{s}^{-1}$, neutrino magnetic moment and neutrino milli-charge fraction at the current bounds from direct experimental searches: $\mu_\nu = 2.9 \times 10^{-11} \mu_B$ [28] and $|\delta_Q| = 1.1 \times 10^{-12}$ [45], respectively. Overlaid are the SM $\bar{\nu}_e$ -e and coherent scattering $\bar{\nu}_e$ -N. Quenching effects of nuclear recoils are taken into account.

limits. The physics potentials becomes richer with lower detector threshold.

New detector technologies are necessary to open new windows of measurable energy. The objectives of our current detector R&D program are to develop detectors with modular mass of $\mathcal{O}(1 \text{ kg})$, physics threshold of $\mathcal{O}(100 \text{ eV}_{\text{ee}})$ and background level at threshold of $\mathcal{O}(1 \text{ kg}^{-1} \text{ keV}_{\text{ee}}^{-1} \text{ day}^{-1})$ [13]. Intense research efforts are invested on the operation and optimization and efficiency measurements of Ge-detectors at sub-keV sensitivities [14, 15], crucial to the studies of neutrino-nucleus coherent scattering and to light Dark Matter searches discussed in the the following Sections.

Complementary to and supporting the neutrino physics and low energy detector programs is the acquisition of low background techniques crucial for the low count-rate experiments. Radio-purity levels of various hardware components were measured with different techniques. In particular, the TEXONO-CIAE group explored a new arena and performed trace contamination measurements on crystal and liquid scintillator materials with accelerator mass spectrometry techniques [16].

3.3.1 Neutrino Electromagnetic Properties

An avenue of BSM is the study of possible neutrino electromagnetic interactions [17] on atomic target A , via the interaction:

$$\bar{\nu}_e + A \rightarrow \nu_X + A^+ + e^- . \quad (1)$$

The target can be taken as free electrons at T above the atomic energy scale. Otherwise, atomic physics effects have to be taken into account [18].

The neutrino magnetic moment (μ_ν) is an intrinsic neutrino property that describes possible neutrino-photon couplings via its spin [19, 11]. The helicity is flipped in μ_ν -induced interactions. Observations of μ_ν at levels relevant to present or future generations of experiments would strongly favor the case of Majorana neutrinos [20]. The differential cross-section with reactor $\bar{\nu}_e$ is depicted in Figure 2b, and is given by

$$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} = \frac{\pi\alpha_{em}^2\mu_\nu^2}{m_e^2} \left[\frac{1 - T/E_\nu}{T}\right] . \quad (2)$$

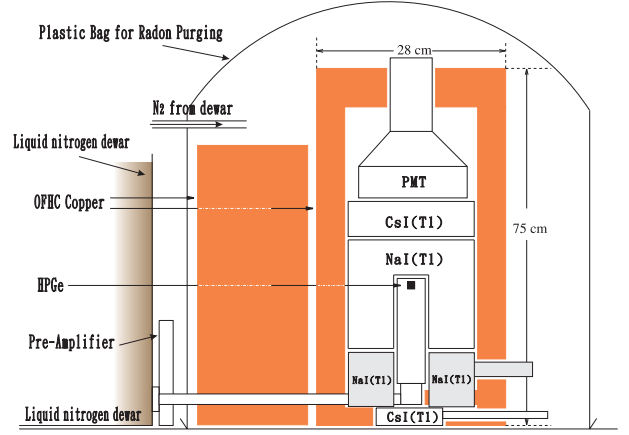


Fig. 3: Schematic layout of the Ge-detector with its anti-Compton detectors as well as inner shieldings and radon purge system. This is the baseline design for Ge-experiments at KSNL and CDEX-1.

above the atomic energy regions ($T > 10 \text{ keV}$ for Ge). The μ_ν contributions are enhanced at low energy with modifications of the atomic binding energy effects [18, 21, 22].

The neutrino spin-flavor precession (SFP) mechanism, with or without matter resonance effects in the solar medium, has been used to explain solar neutrino deficit [23]. This scenario is compatible with all solar neutrino data before 2003 until the terrestrial KamLAND experiment selected the scenario of neutrino oscillation at large mixing angle [24] as *the* solution to the solar neutrino problem [3].

The TEXONO program pioneered the studies of neutrino physics in the low energy ($T \ll 1 \text{ MeV}_{\text{ee}}$) regime [11]. The μ_ν -experiment adopted an ultra-low-background high-purity germanium detector of mass 1.06 kg surrounded by NaI(Tl) and CsI(Tl) crystal scintillators as anti-Compton detectors, as schematically depicted in Figure 3. The setup was placed in the inner volume within the shielding structure of Figure 1b. A detection threshold of $5 \text{ keV}_{\text{ee}}$ and a background level of $1 \text{ kg}^{-1} \text{ keV}_{\text{ee}}^{-1} \text{ day}^{-1}$ at KSNL near threshold were achieved.

The reactor $\phi(\bar{\nu}_e)$ below 2 MeV is poorly modelled and contributed to systematic uncertainties [25] to earlier experiments at the MeV_{ee} range [26]. At $T \ll E_\nu \sim \text{MeV}_{\text{ee}}$, the potential μ_ν -signal rates is much increased due to the $1/T$ dependence of Eq. 2, and is significantly higher

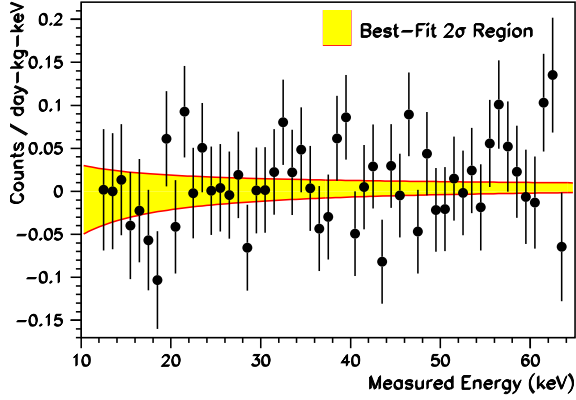


Fig. 4: The residual plot on the combined Reactor ON data over the OFF-background spectra. The allowed 2σ -band for the search of neutrino magnetic moments is superimposed [11].

than the SM $\bar{\nu}_e$ -e “background” making its uncertainties less important. The μ_ν -rate is mostly independent of E_ν at $T \sim 10$ -100 keV_{ee}, such that the μ_ν -rates depend only on the well-known total reactor neutrino flux but not the details of $\phi(\bar{\nu}_e)$, thereby reducing the systematic uncertainties.

Based on 570.7 and 127.8 days of Reactor ON and OFF data, respectively, a limit of

$$\mu_\nu(\bar{\nu}_e) < 7.4 \times 10^{-11} \mu_B \quad (3)$$

at 90% confidence level (CL) was derived. This result improved over existing limits [26] and probed the μ_ν -SFP scenario at the relevant range to the solar neutrino problem [23]. The residual Reactor ON–OFF spectrum is displayed in Figure 4.

An analogous process to μ_ν -interactions is the neutrino radiative decay [27] $\nu_i \rightarrow \nu_j + \gamma$ where a change of the neutrino helicity-states takes place and a final-state real photon is produced. The decay rate Γ_{ij} and the decay lifetime τ_{ij} is related to μ_{ij} via

$$\Gamma_{ij} = \frac{1}{\tau_{ij}} = \frac{1}{8\pi} \frac{(m_i^2 - m_j^2)^3}{m_i^3} \mu_{ij}^2, \quad (4)$$

where $m_{i,j}$ are the masses for $\nu_{i,j}$. The μ_ν -limit

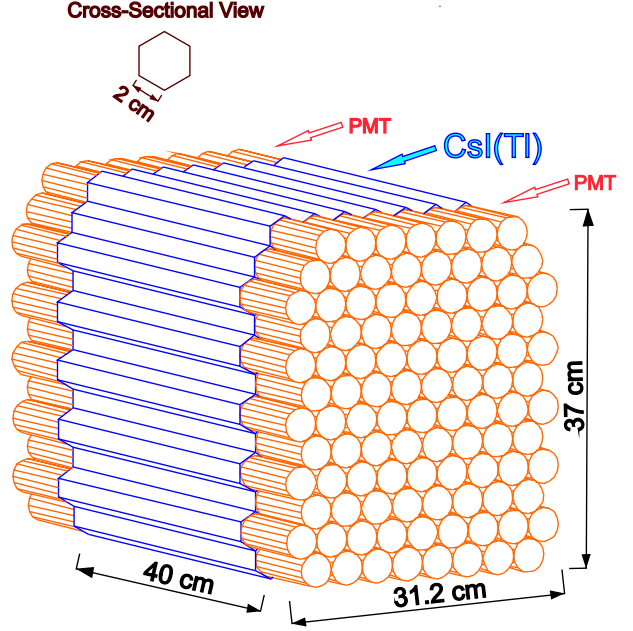


Fig. 5: Schematic drawing of the CsI(Tl) scintillating crystal array for the KSNL $\bar{\nu}_e$ -e scattering measurements [12]. Light output is recorded by PMTs at both ends.

in Eq. 3 translates to indirect bounds:

$$\begin{aligned} \frac{\tau_{13}}{m_1^3}(\text{I} : \nu_1 \rightarrow \nu_3) &> 3.2 \times 10^{27} \text{ s/eV}^3 \\ \frac{\tau_{23}}{m_2^3}(\text{I} : \nu_2 \rightarrow \nu_3) &> 1.2 \times 10^{27} \text{ s/eV}^3 \quad (5) \\ \frac{\tau_{21}}{m_2^3}(\text{N/I} : \nu_2 \rightarrow \nu_1) &> 5.0 \times 10^{31} \text{ s/eV}^3 \end{aligned}$$

for the normal(N) or inverted(I) neutrino mass hierarchies [3] at 90% CL, and are much more stringent than those from the direct search experiments.

Experiments with similar baseline design of Figure 3 are further pursued by the GEMMA experiments at the Kalinin Reactor in Russia, and the current μ_ν -limit [28] exceeds that of Eq. 3. Additional work on the KSNL Ge-data by the TEXONO group derived the flux and placed new constraints on the magnetic moments of ν_e [29], as well as on possible axion emissions from the reactor [30]. Another analysis studied the production and decay of the $^{73}\text{Ge}^*(1/2^-)$ metastable states and placed constraints on neutral-current excitation cross-sections [31].

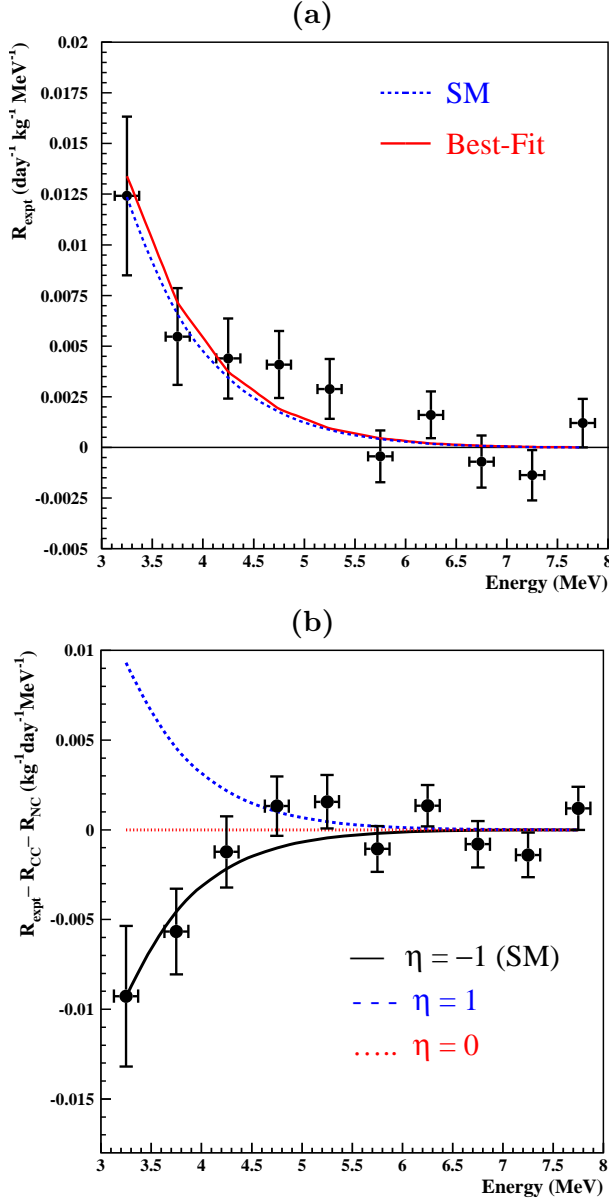


Fig. 6: (a) The combined residual spectrum of Reactor ON data over background [12] in the 3–8 MeV_{ee} energy region. The blue and red lines correspond to the SM expectations and to the best-fit of the data, respectively, showing excellent agreement. (b) The measurement of interference term based on a residual spectrum of subtracting the charged- and neutral-currents contributions from the data, in the 3–8 MeV_{ee} energy range. The scenario of (no,constructive,destructive)-interference is denoted by $\eta=(0,1,-1)$. The measurements verify the SM expectation of $\eta = -1$.

3.3.2 Neutrino-Electron Elastic Scattering

The TEXONO program has provided the best cross-section measurement on two of the fundamental leptons in Nature – $\bar{\nu}_e$ with electrons [12]:

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^- . \quad (6)$$

Reactor $\bar{\nu}_e$ provides a unique laboratory to measure neutrino-electron scattering, and therefore probe electro-weak physics [32] at the MeV momentum transfer range. The $\bar{\nu}_e$ -e interaction, together with the analogous ν_e -e studied with accelerator neutrinos [33], are among the few processes which proceed via charged- and neutral-currents *and* their interference channel. The SM cross-section can be written as:

$$\left[\frac{d\sigma}{dT}(\bar{\nu}_e e) \right]_{SM} = \frac{G_F^2 m_e}{2\pi} \cdot [(g_V - g_A)^2 + (g_V + g_A + 2)^2 \left(1 - \frac{T}{E_\nu} \right)^2 - (g_V - g_A)(g_V + g_A + 2) \frac{m_e T}{E_\nu^2}] . \quad (7)$$

The SM assignments to the electroweak coupling constants are:

$$g_V = -\frac{1}{2} + 2 \sin^2 \theta_W \quad \text{and} \quad g_A = -\frac{1}{2} , \quad (8)$$

where $\sin^2 \theta_W$ is the weak mixing angle.

A scintillating CsI(Tl) crystal detector array [12, 34], as depicted in Figure 5, was constructed for this measurement. The detector is as a proton-free target, with modules packed into a matrix array, having minimal inactive dead space due to the teflon wrapping sheets. A total of 12×9 array was deployed giving a total mass of 187 kg. Each crystal module is 40 cm in length with light output read out by photo-multipliers (PMT) at both ends. The sum of the normalized PMT signals provides the energy, while their difference defines the longitudinal location. Therefore, event reconstruction in three-dimension is achieved. The fiducial volume was defined to be the inner crystals with a separation of >4 cm from the PMTs at both ends.

Reactor ON/OFF data, of 29882/7369 kg-days strength were taken. The Reactor ON over background residual spectrum, as depicted in Figure 6a shows excellent consistency with SM

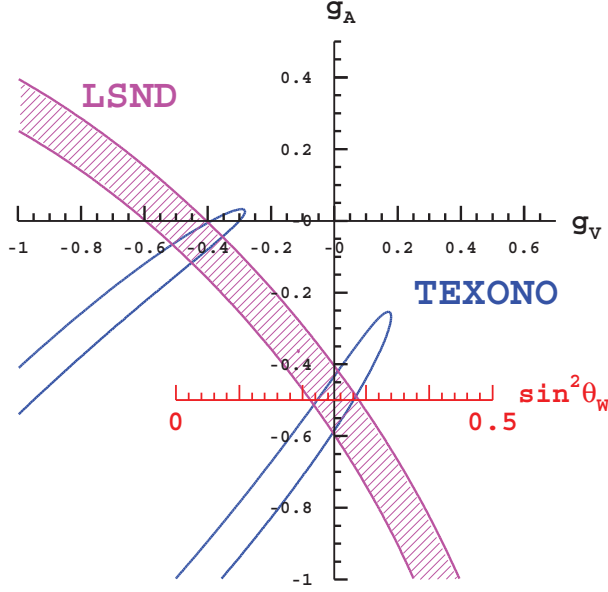


Fig. 7: Best-fit results in (g_V, g_A) space and in the $\sin^2\theta_W$ axis from the TEXONO-CsI(Tl) experiment at KSNL on $\bar{\nu}_e$ -e [12] and the LSND experiment on ν_e -e [33]. The allowed regions are defined by their corresponding statistical uncertainties.

predictions. The ratio of experimental to SM cross-sections of

$$\frac{R_{\text{expt}}(\nu)}{R_{\text{SM}}(\nu)} = 1.08 \pm 0.21(\text{stat}) \pm 0.16(\text{sys}) \quad (9)$$

was measured. After accounting for the charged- and neutral-current components, the SM destructive interference in $\bar{\nu}_e$ -e interactions was verified, as illustrated in Figure 6b.

Constraints on the electroweak parameters (g_V, g_A) were placed, as illustrated in Figure 7. The corresponding weak mixing angle at the squared 4-momentum transfer range of $Q^2 \sim 3 \times 10^{-6} \text{ GeV}^2$ was measured:

$$\sin^2\theta_W = 0.251 \pm 0.031(\text{stat}) \pm 0.024(\text{sys}) \quad (10)$$

The consistency of the data with SM can be translated to bounds on the neutrino charge radius of

$$-2.1 \times 10^{-32} \text{ cm}^2 < \langle r_{\bar{\nu}_e}^2 \rangle < 3.3 \times 10^{-32} \text{ cm}^2 \quad (11)$$

at 90% CL, improving over earlier limits.

3.3.3 Neutrino-Nucleus Elastic Scattering

The current theme of the neutrino physics program at KSNL is on the observation of the elastic scattering between a neutrino and a nucleus (νN) [13, 35] :

$$\nu + N \rightarrow \nu + N \quad (12)$$

It is a fundamental SM-predicted neutrino interaction which has never been observed. It probes coherence effects in electroweak interactions [36], and provides a sensitive test to physics beyond SM. The coherent interaction plays an important role in astrophysical processes and constitutes the irreducible background channel to forthcoming generation of dark matter experiments.

The maximum nuclear recoil energy for a Ge target ($A=72.6$) due to reactor $\bar{\nu}_e$ is about 2 keV_{nr}. The quenching factor (ratio of ionization to total deposited energy), is about 0.2 for Ge in the $< 10 \text{ keV}_{\text{nr}}$ region [14]. Accordingly, the maximum measurable energy for nuclear recoil events in Ge due to reactor $\bar{\nu}_e$ is about 300 eV_{ee}. The typical differential spectrum is given in Figures 2b. At benchmark sensitivities, the expected rate is of $\mathcal{O}(10 \text{ kg}^{-1}\text{day}^{-1})$ with a signal-to-background ratio > 50 .

Improvement of the lower reach of detector sensitivity without compromising background is therefore crucial for such experiments, and are the focuses of our current research.

3.4 Dark Matter Searches

The goal of measuring the neutrino-nucleus coherent scattering process of Eq. 12 at KSNL leads to the development of low threshold Ge-detector with sub-keV sensitivity [14]. This detector technology naturally brings the Collaboration to venture into the important arena on direct Dark Matter searches [13].

Weakly Interacting Mass Particles (WIMPs, denoted by χ) are leading candidates to the Dark Matter Problem in the Universe [37]. The elastic recoils between WIMPs and the nuclei

$$\chi + N \rightarrow \chi + N \quad (13)$$

are the favored channel in direct dark matter search experiments. Consistency with obser-

vations on cosmological structure formation requires that WIMPs should be massive and their motions are non-relativistic. The measurable nuclear recoil energy is therefore small, such that the experimental requirements are similar to those for νN where low detector threshold is crucial.

We opened the sub-keV detector window with pilot “Ultra-Low-Energy” Ge detectors (ULEGe) [13] with modular mass of the order of 10 g. Data taken with a 20 g ULEGe array at an analysis threshold of 220 eV_{ee} at KSNL [38], a surface laboratory hardly appropriate for such experiments, already allowed the probing of new parameter space in the “Light WIMPs” region of several GeV in mass.

Our early efforts on WIMP searches inspired advances in point-contact germanium detectors (PCGe) by a US group based on an earlier design [39], realizing sub-keV sensitivity with a modular mass at kg-scale. The CoGeNT experiment subsequently reported possible allowed regions for light WIMPs [40] turning this into a domain of intense interest. The TEXONO group performed a measurement at KSNL with a PCGe with p-type germanium (p-PCGe) of 840 g fiducial mass [41], following the baseline setup of Figure 3.

Crucial to this study is the bulk-surface events differentiation at the sub-keV range [14, 42]. As illustrated with Figure 8a, the surface background events in p-PCGe detectors, exhibit slower rise-time and partial charge collection compared to bulk events which are candidates for χN -signals. The measured rise-time distribution is depicted in Figure 8b. In the contrary, n-type PCGe does not have anomalous surface layer and shows uniform rise-time, as shown in Figure 8c.

Selection schemes of bulk signal events in p-PCGe were devised, and the corresponding signal-retaining and background-rejecting efficiencies were measured [42]. Our results indicated deficiencies of the previous approaches, and the excess events interpreted to be WIMP candidate signals are due to incomplete correction of the leakage of surface background into the bulk signal samples. The exclusion plot of χN spin-independent cross-section versus WIMP-mass is displayed in Figure 9a.

Light WIMP searches started as an ex-

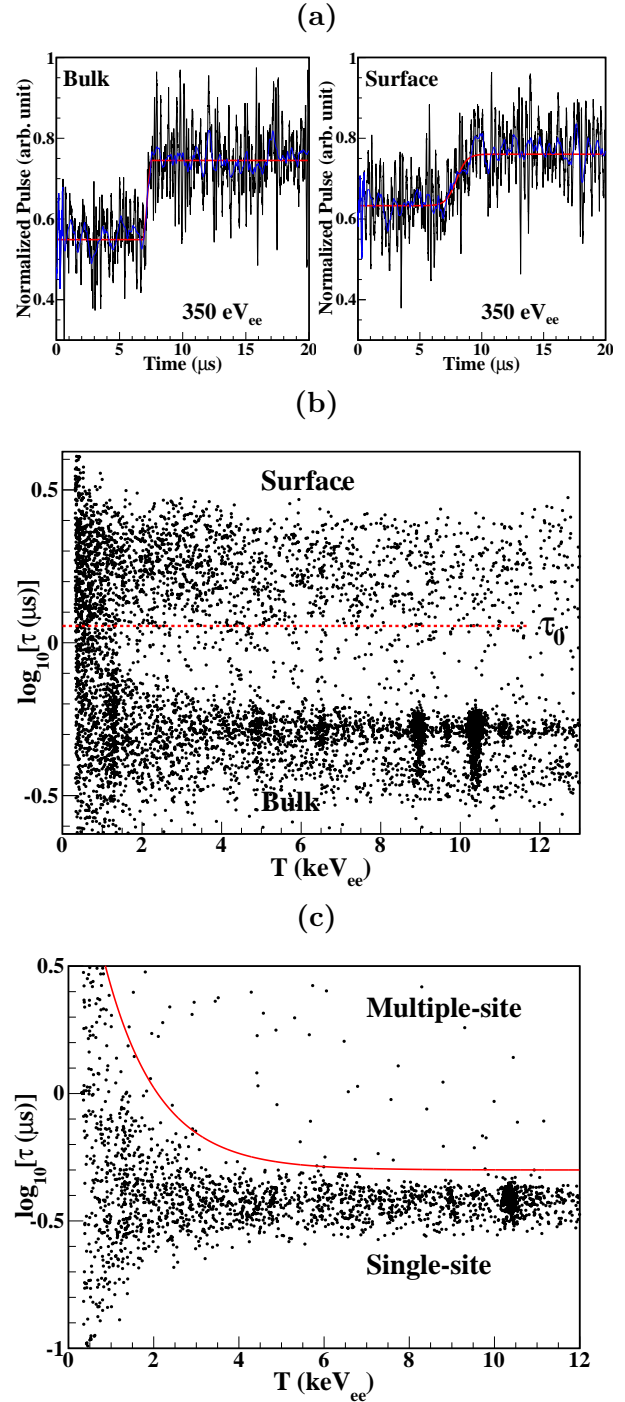


Fig. 8: (a) Measured pulse profiles for typical Bulk and Surface events [14, 42] in p-PCGe. (b) The rise-time(τ) distribution in p-PCGe. The selection criteria of signal events in the Bulk is defined by the cut at τ_0 . (c) The rise-time(τ) distribution in n-PCGe. There are no anomalous surface events.

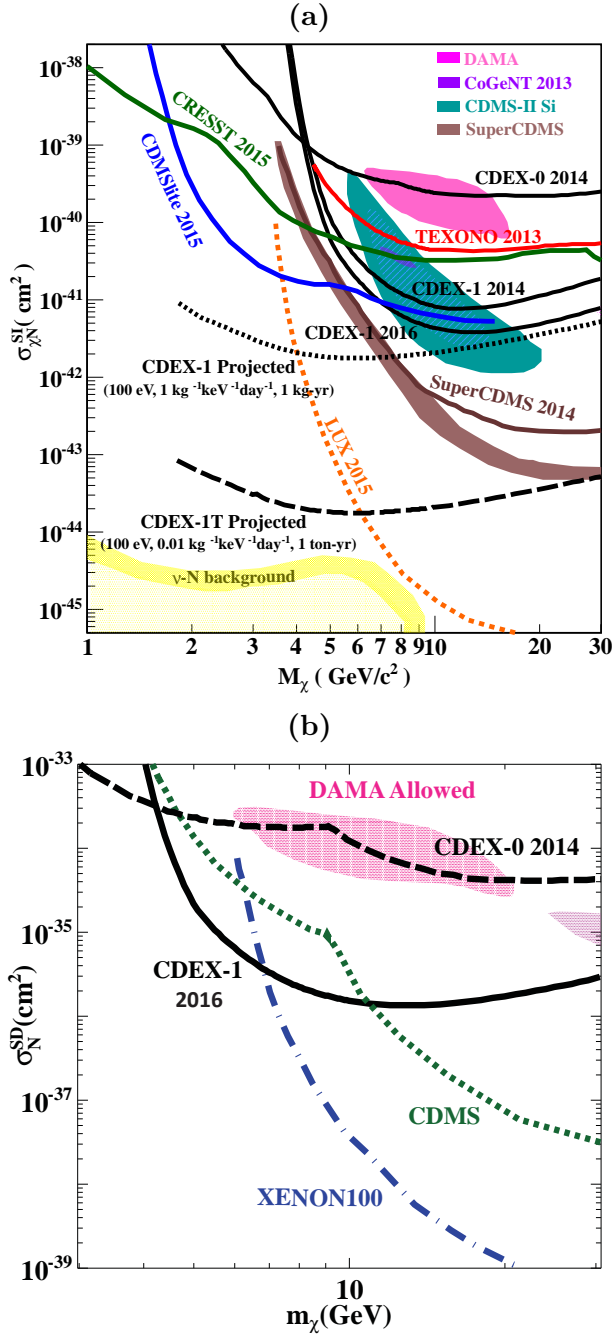


Fig. 9: Exclusion plots of χN (a) spin-independent and (b) spin-dependent interactions, showing the TEXONO [41] and CDEX [50, 53] results together with the allowed regions and limits from other benchmark experiments [37].

ploratory by-product of the TEXONO program at KSNL on sub-keV Ge-detectors and neutrino-nucleus coherent scattering. As we shall discuss in Section 4, these efforts would inspire and catalyze the realization of the deepest and largest underground scientific facility at CJPL.

3.5 Theory Programs

The TEXONO experimental program and the unique data at KSNL triggered several theory research directions, and establishes fruitful collaborations among the experimental and theory researchers.

One direction, spearheaded by the TEXONO Turkish groups, is to study the constraints from neutrino-electron scattering to BSM models, especially those where data at low- T , such as those from KSNL, would provide enhanced sensitivities. These include [43] generic non-standard interactions, unparticle physics, non-commutative physics and dark photon physics.

Another line is rooted in our current experimental theme and uniqueness of using novel germanium detectors with sub-keV sensitivities and very good energy resolution to explore neutrino and dark matter physics. This technique excels in probing experimental signatures at the “atomic” energy range and with possible spectral structures due to atomic ionization. A pilot investigation [22] set the stage on the subsequent studies of “atomic ionization” cross-sections. Theorists in Taiwan (J.W. Chen and C.P. Liu and their groups), through collaboration with the TEXONO group, introduced state-of-the-art theoretical tools in atomic physics (MCRRPA—Multi-Configuration Relativistic Random-Phase Approximation [44]) leading to a series of results on experimental signatures due to neutrino electromagnetic effects [18, 45, 46], illustrated in the differential cross-sections of Figure 2b.

Some of the results provide positive feedback to the experiment programs and data interpretation, examples of which include:

1. Studies of the “neutrino milli-charge” probe possible helicity conserving QED-like interactions. Finiteness of the neutrino charge fraction (δ_Q) would imply neutrinos are Dirac particles. It was demonstrated that atomic ionization effects due to δ_Q lead to big enhancement in cross-sections [45], as

depicted in Figure 2b. The known ratios of peaks at discrete binding energies provide smoking gun signatures for positive observations.

2. A massive sterile neutrino can have transition- μ_ν and interact with matter to become a light SM neutrino. If it is non-relativistic, as in the case of a dark matter candidate, the interaction would have a cross-section pole and enhancement at half its mass [46]. Constraints were derived from KSNL data.
3. The quantum mechanical coherence effects of electroweak interaction can be quantitatively studied, using the νN scattering of Eq. 12. We derived how the degree of coherence would vary with realistic neutrino sources, target materials and detection threshold [36], showing how the forthcoming experimental projects can complement each other.

4 China Jinping Underground Laboratory and the CDEX Research Programs

4.1 Foundation

The potentials of dark matter experiments were immediately realized after initial sub-keV measurements achieved with germanium detectors [13]. While the main thrust of the Collaboration remains on the development of the detector techniques and reactor neutrino physics at KSNL where dark matter physics is a by-product, the TEXONO-Tsinghua University (THU) group explored the means to turn it into dedicated experiments.

An underground site is therefore mandatory. The THU group spearheaded a pilot project of installing a 5 g ULEGe detector at the Yangyang Underground Laboratory in Korea in 2004, supported by the KIMS group as host of that Facility.

A construction road tunnel was completed in 2008 under the Jinping mountains in Sichuan province in China to facilitate the construction of the numerous hydro-electric power facilities in that region – the flagship project is the Jinping-

I dam which, at 305 m, is the tallest dam in the world. The physics communities in China immediately recognized the opportunities and potentials. By 2010, agreement was made between the site owner Yalong River Hydropower Development Company and THU to jointly develop and operate an underground laboratory facility the China Jinping Underground Laboratory (CJPL) [47]. Civil engineering proceeded in full swing.

The TEXONO-THU group got significant boost in its manpower and resource pool to match the expanding engineering demands and scientific program. The group evolved and emerged to form and lead a new CDEX (China Dark matter EXperiment) Collaboration focusing on, in its start-up phase, dark matter experiments at CJPL. The CDEX program is led by Kang Ke-Jun (a former Vice President of THU). The TEXONO Collaboration became a founding partner and participant of this endeavour.

4.2 The Facility

The Facility CJPL [48] is located in Sichuan, China, and was inaugurated in December 2012. With a rock overburden of about 2400 meter, it is the deepest operating underground laboratory in the world. The muon flux is measured to be $(2.0 \pm 0.4) \times 10^{-10} \text{cm}^{-2} \text{s}^{-1}$ [49], suppressed from the sea-level flux by a factor of 10^{-8} . The drive-in tunnel access can greatly facilitate the deployment of big experiments and large teams. Supporting infrastructures of catering and accommodation, as well as office and workshop spaces, already exist. All these merits make CJPL an ideal location to perform low count-rate experiments.

As depicted schematically in Figure 10a, the completed CJPL Phase-I consist of a laboratory hall of dimension 6 m(W) \times 6 m(H) \times 40 m(L). This space is currently shared by the CDEX [50] and PandaX[51] dark matter experiments, as well as a general purpose low radio-purity screening facility.

Additional laboratory space for CJPL Phase-II [52], located about 500 m from the Phase-I site, is currently under construction. It will consist of four experiment halls each with dimension 14 m(W) \times 14 m(H) \times 130 m(L), connected by an array of access tunnels. The schematic layout of

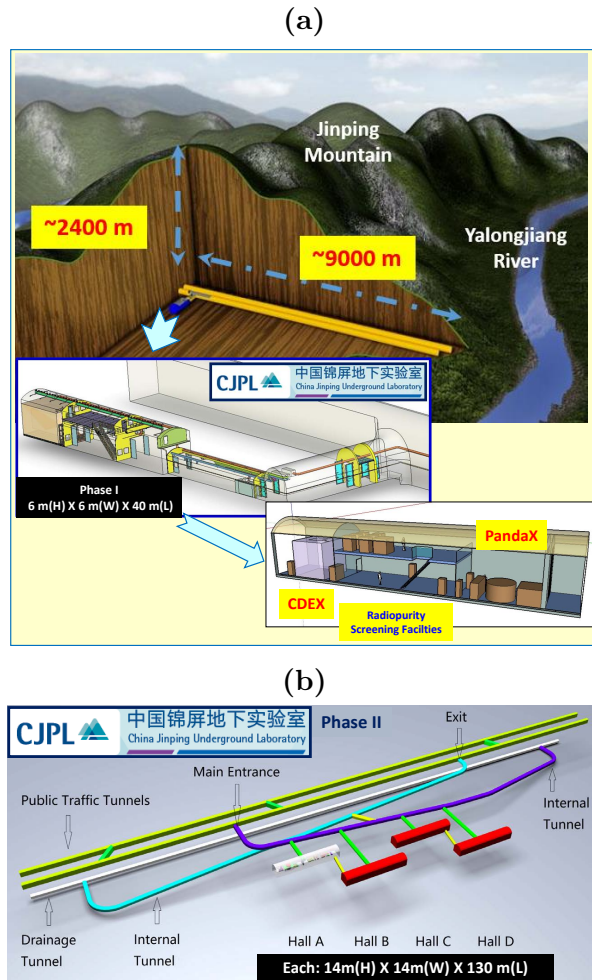


Fig. 10: Schematic diagram of (a) CJPL Phase-I inaugurated in 2012, showing the space allocation to the CDEX and PandaX Dark Matter experiments, as well as to the radio-purity screening facilities, (b) CJPL Phase-II scheduled to complete by early 2017, showing the four experimental halls and the tunnel systems.

CJPL-II is displayed in Figure 10b. Upon the scheduled completion by early 2017, CJPL will be, in addition, the largest underground laboratory by volume in the world.

4.3 CDEX Dark Matter Program

The scientific theme of CDEX program [50] is to pursue studies of light WIMPs with p-PCGe. It is one of the two founding experimental programs at CJPL.

4.3.1 First Generation CDEX Experiments

Following schematics of the shielding structures and target detectors depicted in, respectively, Figures 1b&3, the first-generation experiments adopted the KSNL baseline design [11, 38] of single-element “1-kg mass scale” p-PCGe enclosed by NaI(Tl) crystal scintillator as anti-Compton detectors, further surrounded by passive shieldings and radon purge system. Active cosmic-ray vetos are not necessary at this depth.

The pilot CDEX-0 measurement is based on the 20 g ULEGe detector array [38] at an exposure of 0.784 kg-days and a threshold of 177 (eV_{ee}) [53]. The CDEX-1 experiment adopts a p-PCGe detector of mass 1 kg. The latest results are based on an analysis threshold of 475 eV_{ee} with an exposure of 335.6 kg-days[50]. After suppression of the anomalous surface background events and measuring their signal efficiencies and background leakage factors with calibration data [42], all residual events can be accounted for by known background models. The spectra are depicted in Figures 11a,b&c. Dark Matter constraints on χ N spin-independent cross-sections were derived for both data set, and are displayed in Figures 9a&b, together with other selected benchmark results [37]. In particular, the allowed region from the CoGeNT[40] experiment is probed and excluded with the CDEX-1 results.

Analysis is currently performed on CDEX-1 data set with year-long exposure. Annual modulation effects as well as other physics channels are being studied. New data is also taken with an upgraded p-PCGe with lower threshold.

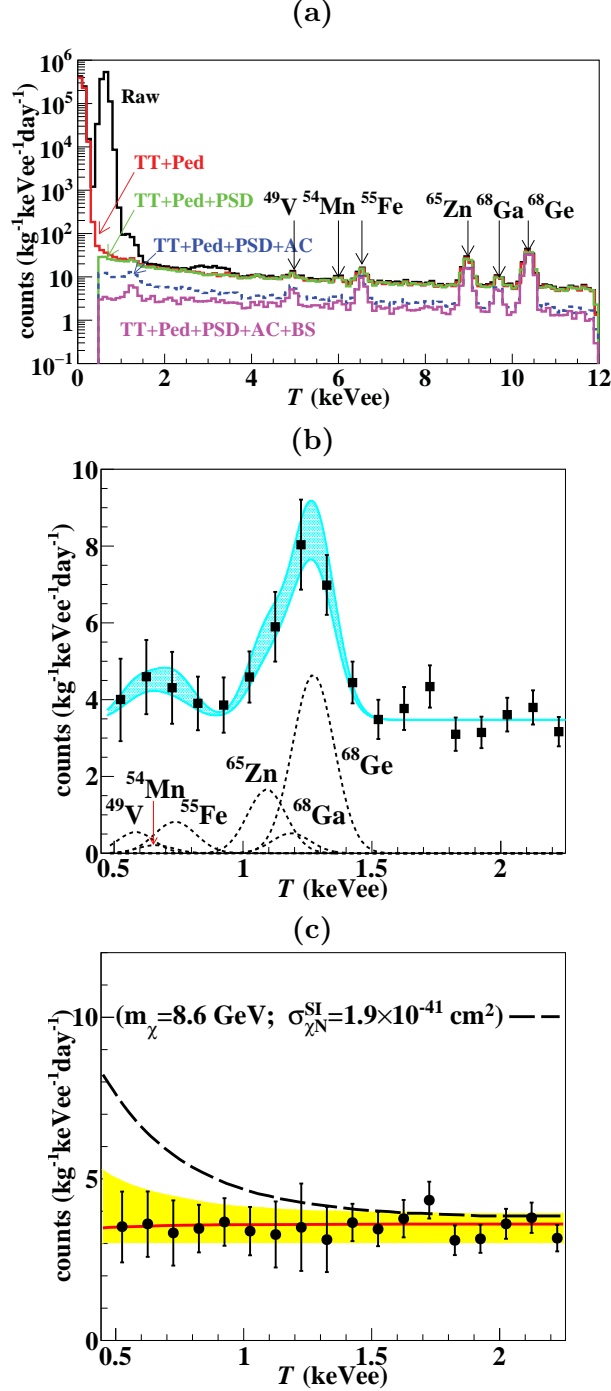


Fig. 11: (a) Background spectra of the CDEX-1 measurement [50] at their various stages of selection: basic cuts (TT+Ped+PSD), Anti-Compton (AC) and Bulk (BS) events. (b) All events can be accounted for with the known background channels – L-shell X-rays and flat background due to ambient high energy γ -rays. (c) Residual spectrum with known background channels subtracted. An excluded χ N recoil spectrum with parameters listed is superimposed.

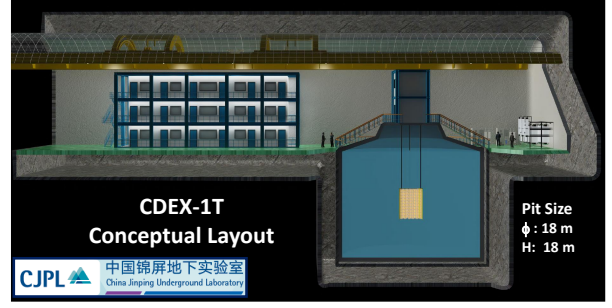


Fig. 12: Conceptual configuration of a future CDEX-1T experiment at CJPL-II, showing the pit in which the detector, cryogenic liquid and water shielding can be placed.

4.3.2 Current Efforts and Future Goals

The long-term goal of the CDEX program will be a ton-scale germanium experiment (CDEX-1T) at CJPL for the searches of dark matter and of neutrinoless double beta decay ($0\nu\beta\beta$) [54]. A pit of diameter 18 m and height 18 m is being built at one of the halls of CJPL-II to house such an experiment, as illustrated in Figure 12. The conceptual design is a central region for germanium detector arrays, surrounded by cryogenic liquid and/or water shielding.

Towards this ends, the “CDEX-10” prototype has been constructed with detectors in array structure having a target mass at the 10-kg range. This would provide a platform to study the many issues of scaling up in detector mass and in improvement of background and threshold. The detector array is shielded and cooled by a cryogenic liquid. Liquid nitrogen is being used, while liquid argon is a future option to investigate, which may offer the additional potential benefits of an active shielding as anti-Compton detector.

In addition, various crucial technology acquisition projects are pursued, which would make a ton-scale germanium experiment realistic and feasible. These include:

1. detector grade germanium crystal growth;
2. germanium detector fabrication;
3. isotopic enrichment of ⁷⁶Ge for $0\nu\beta\beta$;
4. production of electro-formed copper, eventually underground at CJPL.

The first detector fabricated by the CDEX program from commercial crystal that matches expected performance is scheduled to be installed at CJPL in 2016. It allows control of assembly materials placed at its vicinity, known to be the dominant source of radioactive background, while providing an efficient test platform of novel electronics and readout schemes. The benchmark would be to perform light WIMP searches with germanium detectors with “ $0\nu\beta\beta$ -grade” background control. This configuration would provide the first observation (or stringent upper bounds) of the potential cosmogenic tritium contaminations in germanium detectors, from which the strategies to suppress such background can be explored.

The projected sensitivity in χN spin-independent interactions for CDEX-1T is shown in Figure 9a, taking a realistic minimal surface exposure of six months.

The studies of $0\nu\beta\beta$ can address the fundamental question on whether the neutrinos are Dirac or Majorana particles [54]. The current generation of ^{76}Ge - $0\nu\beta\beta$ experiments [55] are among those with leading sensitivities in the pursuit. The objective of a possible “CDEX-1T@CJPL-II” experiment in $0\nu\beta\beta$ will be to achieve sensitivities sufficient completely cover the inverted neutrino mass hierarchy [3]. An international network is emerging towards the formation of a proto-collaboration to pursue this challenging goal.

Such visions stand on several important merits and deserve serious considerations. The overburden at CJPL is among the deepest in the world, essential for the unprecedented background control requirements for such a project. Being a new laboratory, there are ample space for possible Ge-crystal growth and detector fabrication and copper production, in addition to the pit for the main detector and shielding in Figure 12. Furthermore, the crucial aspect of this project is the necessity of delivering industrial standard practices and control during the mass production of detector hardware. This requirement matches well to the profile of the CDEX-THU group, being closely associated with an industry [56] which has strong experience in the construction and deployment of large radiation detector systems for international clients.

5 Prospects

The TEXONO Collaboration was launched from an operating system without previous traditions and infra-structures and experience of running its own particle physics experiments. With almost two decades of dedications and persevering efforts, the Collaboration has grown and thrived and emerged into having a recognizable presence in the world stage. It has contributed to the advances and opening of new and innovative avenues in low energy neutrino physics, light dark matter searches as well as low threshold germanium detector techniques. The TEXONO-DNA is propagating in China, India and Turkey as the alumni members are setting up the first-generation research efforts on the low-background experimentation in these countries.

The observation of neutrino-nucleus coherent scattering is the top-priority science goal at KSNL. Scaling that summit would require further advancing the technologies and techniques of the germanium detectors. While the realization of the underground facility CJPL – and the implicit investment and commitment – is an impressive (and intimidating) feat on its own, the science programs are still in their embryonic and formative stage. The TEXONO group is at a favorable vantage position to explore and define and formulate the future research programs at CJPL which may bring the Collaboration to higher grounds. In particular, discussions and studies have been initiated on a ton-scale ^{76}Ge $0\nu\beta\beta$ program at CJPL.

There are grounds to expect that the future of the TEXONO story, in spite of – or perhaps because of – not having the detailed landscape charted out yet, would be as exciting and rewarding.

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